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DIGITIZATION AND ANALYSIS OF PHOTOGRAPHIC IMAGES OF STRATOSPHER--ETC(U)

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DIGITIZATION AND ANALYSIS OF PHOTOGRAPHIC IMAGES OF STRATOSPHERIC SMOKE TRAILS

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AD A093926

30 July 1980

Final Report for Period 01 September 1978 - 30 June 1980

Approved for public release; distribution unlimited

PREPARED FOR

AIR FORCE GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
HANSCOM AFB, MASSACHUSETTS 01731

(9) Final rept. 1 Sep 78-30 Jun 80

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER (19) (18) AFGL-TR-80-0230	2. GOVT ACCESSION NO. AD-A093926	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) (6) DIGITIZATION AND ANALYSIS OF PHOTOGRAPHIC IMAGES OF STRATOSPHERIC SMOKE TRAILS.		5. TYPE OF REPORT & PERIOD COVERED Final Report 01 Sep 78 - 30 Jun 80
		6. PERFORMING ORG. REPORT NUMBER (14) PhM-02-80
7. AUTHOR(s) (10) Christian A. Trowbridge		8. CONTRACT OR GRANT NUMBER(s) (15) F19628-78-C-0227
9. PERFORMING ORGANIZATION NAME AND ADDRESS PhotoMetrics, Inc. 442 Marrett Rd Lexington, MA 02173		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102F (16) 668705AS (17)
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Geophysics Laboratory Hanscom AFB, Massachusetts 01731 Monitor: A.F. Quesada/LKD		12. REPORT DATE (11) 30 July 1980
		13. NUMBER OF PAGES 26
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) (12) 21		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Atmospheric Wind Field
Smoke Trail Tracers
Stratosphere
Photographic Triangulation
Reduction of Photographic Images

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A program of determination of horizontal wind profiles in the stratosphere is described. Photographic records of sunlight-scattering smoke trail tracers released from rockets were digitized, with the film plane coordinates of the trail centers recorded for input to a computer program that calculates spatial locations of sequences of trail points by vector triangulation.

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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

392596

20. Abstract (continued)

Star field photographs provided highly accurate camera orientations for calibration of the triangulation program. Reconstructed three-dimensional trail positions as a function of time were processed to provide horizontal winds and vertical shear at approximately 10 meter vertical resolution.

FOREWORD

The program described here involved the operation (and maintenance) of the AFGL Trail Digitization System at PhotoMetrics, Inc., to reduce photographic records of stratospheric smoke trails to digital form. Pairs of such images were then analyzed to determine time dependent trail positions and subsequently horizontal wind and wind shears.

The author wishes to express thanks to Dr. A.F. Quesada and Mr. W.K. Vickery (Technical Monitors) of AFGL for their continued encourgagement and support, and to C.C. Rice who made important contributions to this report.

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SUMMARY AND OVERVIEW

The objective of the work reported here is to provide stratospheric wind information from precision photographic triangulation to smoke trails released from rockets. This involves the operation and maintenance of the AFGL Trail Digitization System and subsequent reduction of wind profiles from the digitized smoke trail coordinates. The Digitization System (Ref 1) semi-automatically measures the coordinates of the center line of the smoke trail image; from pairs of such images from spatially-separated remote measurement sites, the time dependent spatial position of the trail is determined, and winds and shears are derivable from these positions (Ref 2).

Section II briefly reviews the smoke trail technique for determination of atmospheric winds, and contains references for further information. This section also describes modifications and improvements made to the existing digitizing system programs and a summary of data analyzed by these methods.

Maintenance of the Trail Digitization System is described in Section III and conclusions and recommendations are in Section IV.

SECTION II

PROCEDURE DEVELOPMENT AND RESULTS

This section enumerates the procedures applied to determine the wind field from photographs of smoke trails released in the stratosphere. This brief review may be supplemented by References 1-4. Also presented are modifications made to the digitizing software and triangulation program, and a summary of data reduced and analyzed.

SMOKE TRAIL TECHNIQUE

The rocket deposited smoke trail method has been utilized for at least 20 years to trace wind speed and direction in the atmosphere. A dense smoke, released from a rocket as it ascends through the atmosphere, is usually transported substantially intact by the wind field for periods of one to two minutes. Photographic records of the trail position as a function of time from a minimum of two observation sites are used to determine by triangulation the time dependent spatial locations of the trail which may be used to calculate horizontal winds as a function of altitude.

Photographs of the trail taken at the same time from two sites are digitized to determine the film plane coordinates of the center of the trail. In principle it is possible to use these photographic projections to reconstruct the spatial location of the trail at that instant in time, given the locations and orientations of the two cameras. In practice there are many pitfalls, some of which are enumerated in References 1 and 2.

Recent advances in technique have greatly improved the accuracy of the smoke trail method. Vector methods of solution have been applied to the problem of accurately determining observation camera parameters (Ref 3). A photograph of the stars in the camera field of view at a precisely known instant in time is digitized to determine the coordinates of the stars in the film plane. Star coordinates together with the camera location (latitude, longitude, and altitude), and the known star locations (right ascension, declination) are utilized to determine camera azimuth, elevation, horizonal tilt, and precise focal length of the lens. Through editing of input star coordinates and iteration of the parameter determinations, accuracies of approximately 0.01 degrees angular standard deviation and 0.01 cm focal length standard deviation may be routinely achieved. Considered as a spatial accuracy, these deviations may be translated approximately 10 meter positional accuracy at typical ranges to the smoke trail of 40 km.

The actual triangulation procedure uses digitized film plane coordinates of the trail as viewed from two sites, the site locations, and the camera orientations derived from the star calibration photographs. An iterative approach using the vector methods of Reference 4 is utilized to determine the minimum error pairing of points of one site with points of the other site. The error which is minimized is the dihedral angular mismatch between planes generated by film plane point line of sight vectors from each site and a line through the two sites. The altitude, latitude, and longitude of intersection (or near intersection) of lines of site vectors for matched points is recorded for subsequent use in determining horizontal wind velocities from time sequential trail positions.

The final portion of the procedure uses the time sequence of trail point positions, usually five times over a period of one minute, and performs a least squares analysis of position versus time to arrive at average horizontal velocities and associated errors. These data may be further analyzed to determine vertical shear of the horizontal wind, and turbulence descriptors such as Richardson number, length scales, and heating rates. Examples of such analysis are contained in References 5-7.

PROGRAM MODIFICATIONS

Numerous modifications were made to the computer software to speed system operations, improve performance, ease operator fatigue, and allow easier operator intervention.

The first changes made were to increase the digitizing rate. This was accomplished by elimination of unnecessary printing and major software changes to allow more rapid convergence of the measurement axis to the position of the desired film optical density threshold. Further enhancement in speed was achieved by decreasing the volume of video information which must be processed for each coordinate pair recorded. The maximum digitizing rate was increased from approximately 200 coordinate measurements per hour to approximately 600 measurements per hour.

Another important program modification involved design and implementation of improved fiducial alignment techniques. The fiducial markers which are exposed onto the data frames by small lights within the camera and which form the basis for all measurements are generally poorly defined, often have rough edges, edges which are not oriented properly (because of misalignment of the exposing lamp with the fiducial mask), or are missing entirely (lamp or timing device failure). Methods have been devised to perform alignment in a manner which remains constant from frame to frame when fiducial markers are present. Alignment when fiducial markers are absent can usually be accomplished utilizing the edges of the data frame mask, but considerable operator intervention is required. A special procedure must be established for each film magazine since the masks in each are not identical.

Further changes have included recognition and correction of a round off error problem in the star digitizer, which greatly increased the accuracy of the camera orientation angles determined from the star calibration photographs; and improvement of the error handling routine. The error recovery routine now allows the digitizing system operator more freedom in his choice of corrective action, permits him to make multiple corrections at one time and to change permanently the scan orientation, and allows more convenient access to the computation routine.

Few changes were made to the triangulation programs as it is considered that this procedure performs within the limits of errors imposed by the uncertainty in camera orientation. The present manual timing procedure for the star calibration exposures with an accuracy of approximately one second probably contributes more than half of the error associated with the camera pointing angles. One-tenth second or better resolution of the exposure timing is essential to reduce these errors.

DATA ANALYSIS

Reduction of the photographic trail image to digital form was performed for the stratospheric trails listed in Table 1.

Each frame was aligned on the scanner using fiducial markers of frame edges such that orthogonality with one axis of the scanner was better than $8\mu m$ over approximately 115 mm and the position of the camera optic axis was located with a repeatability of $\pm 8\mu m$. The maximum increment along the trail from point to point was $48\mu m$, unless otherwise noted.

Trails indicated as dashed consist of up to 10 trail segments each approximately 5 km long separated by spaces of approximately 3 km. These long trails, programmed to release over approximately 15 - 50 km, were often not always usable over the entire length for a variety of reasons. Camera viewing angles optimized for the lower portion of the trail were often much less than adequate for the upper portion, as they resulted in multiple overlapping of the trail in the photographic projection or extreme foreshortening obliterating most detail structure. The last minute change of the launch azimuth of one rocket resulted in reduced photographic coverage from one site; on another rocket the release timer malfunctioned, releasing the trail

Table 1. Summary of Data Digitized

Event Name or Date	Frame	Site	Data
FLORA	14	SEEHORN	SINGLE TRAIL
4 Jun 73	17	SEEHORN	13-19 km
	19	SEEHORN	
	21	SEEHORN	
	23	SEEHORN	
	14	HOTEL	
	17	HOTEL	
	19	HOTEL	
	21	HOTEL	
IRIS	65	SEEHORN	SINGLE TRAIL
6 Jun 73	66	SEEHORN	14-23
	67	SEEHORN	
	68	SEEHORN	
	65	HOTEL	
	66	HOTEL	
	67	HOTEL	
	68	HOTEL	
22 Apr 77	81	T5	DASHED TRAIL
	82	T5	18-37 km
	83	T5	
	84	T5	
	81	TWO BUTTES	
	82	TWO BUTTES	
	83	TWO BUTTES	
	84	TWO BUTTES	
	85	TWO BUTTES	
20 May 78	2	POCOMOKE	DASHED TRAIL
	3	POCOMOKE	16-44 km
	4	POCOMOKE	
	5	POCOMOKE	
	6	POCOMOKE	
	7	POCOMOKE	
	8	POCOMOKE	
	9	POCOMOKE	

Table 1. Summary of Data Digitized (continued)

Event Name or Date	Frame	Site	Data
20 May 78	2	WACHAPREAGUE	
	3	WACHAPREAGUE	
	4	WACHAPREAGUE	
	5	WACHAPREAGUE	
	6	WACHAPREAGUE	
	7	WACHAPREAGUE	
	8	WACHAPREAGUE	
	9	WACHAPREAGUE	
20 May 78	4	POCOMOKE	HIGH RESOLUTION SCANS OF DASH 3 – MAXIMUM INCREMENT = 12μm
	5	POCOMOKE	
	6	POCOMOKE	
	7	POCOMOKE	
	4	WACHAPREAGUE	
	5	WACHAPREAGUE	
	6	WACHAPREAGUE	
	7	WACHAPREAGUE	
22 May 78	41	POCOMOKE	DASHED TRAIL 29-42 km
	42	POCOMOKE	
	43	POCOMOKE	
	44	POCOMOKE	
	45	POCOMOKE	
	46	POCOMOKE	
	47	POCOMOKE	
	41	WACHAPREAGUE	
	42	WACHAPREAGUE	
	43	WACHAPREAGUE	
	44	WACHAPREAGUE	
	45	WACHAPREAGUE	
	46	WACHAPREAGUE	
	47	WACHAPREAGUE	
12 Sep 78	11	OBSERVATORY	DASHED TRAIL
	12	OBSERVATORY	
	13	OBSERVATORY	
	14	OBSERVATORY	
	15	OBSERVATORY	
	16	OBSERVATORY	

Table 1. Summary of Data Digitized (continued)

Event Name or Date	Frame	Site	Data
12 Sep 78	17	OBSERVATORY	
	18	OBSERVATORY	
	19	OBSERVATORY	
	20	OBSERVATORY	
	11	TWIN LAKES	
	12	TWIN LAKES	
	13	TWIN LAKES	
	14	TWIN LAKES	
	15	TWIN LAKES	
	16	TWIN LAKES	
	17	TWIN LAKES	
	18	TWIN LAKES	
	19	TWIN LAKES	
	20	TWIN LAKES	

at higher altitude and thus resulting in reduced coverage; and for still another trail uncertainty in camera orientation made reduction of the higher altitude dashes inaccurate.

High resolution digitization was performed for one dash of trail 20 May 78 using a $12\mu m$ increment instead of $48\mu m$ to check the digitization system closer to its $4\mu m$ resolution limit and to test the triangulation and velocity programs at this finer scale. Results of the test are discussed later in this section.

Star calibration frames digitized are shown in Table II. Hardware constraints presently dictate the accuracy of the measurement of the coordinates of the center of the star tracks. The number of coordinate pairs which may be sampled (and stored) along the long star image is limited, and thus the distance ΔS between samples depends on the length of the star track. The repeatability of the measurement of the coordinates of the center of the star is approximately $\pm \Delta S$ in length along the track. This may be related to the x and y repeatability by $\pm \Delta S \cos \alpha$, $\pm \Delta S \sin \alpha$ respectively, where α is the angle between the track and the horizontal of the calibration photograph.

Reduction of horizontal and wind components and shears has been accomplished for all data in Table 1 with the exception of the 9 Sep 78 trail. Altitude resolution is approximately 10 meters for altitudes below 30 km and 15 meters from 30 to 40 km. The decrease in resolution with increasing range to the trail has been compensated for in the digitization process for the 9 Sep 78 trail by using smaller digitization increments with increasing altitude, with the result that resolution for the data should be nearly 10 meters even at the highest altitudes.

Typical of the data frame pairs used in the reduction are the frames of trail 20 May 78 shown in Figs 1 and 2. Profiles of the easterly and northerly components of the horizontal wind for dash 3 of this trail dervied from a time series of five frame pairs spanning 60 sec are shown in Figs 3 and 4. The previously mentioned test of

Table 2. Summary of Star Frames Digitized

Event Name or Date	Frame	Site	Maximum Error (Along Star Track)
FLORA	9	HOTEL	± 24μm
4 Jun 73	11	SEEHORN	
IRIS	63	HOTEL	± 20μm
6 Jun 73	63	SEEHORN	
22 Apr 77	99	T5	± 24μm
	99	TWO BUTTES	
20 May 78	1	WACHAPREAGUE	± 20μm
22 May 78	20	WACHAPREAGUE	
	1	POCOMOKE	
12 Sep 78	10	OBSERVATORY	± 16μm

higher resolution digitization was performed forthis particular data, with the resulting winds shown in Figs 5 and 6. Qualitative agreement, with the exception of a few determinations near each end, is good However, an expected decrease in standard deviation in the wind measurements did not occur. Inspection of the high resolution triangulation results showed that although the average altitude increment was reduced by a factor of three as expected, the standard deviation of this quantity went down by only 50 percent. Evidence of improper pairing of points was present which produce discontinuities and high shears. Retriangulation with more strict matching criteria did not improve the results. This degradation in results with the production of artificially high shears is probably caused by an attempt to reduce data at a resolution far below the limits set by precision of the camera orientation and focal length determinations. That limit for this particular data set is about 10 - 15 meters.

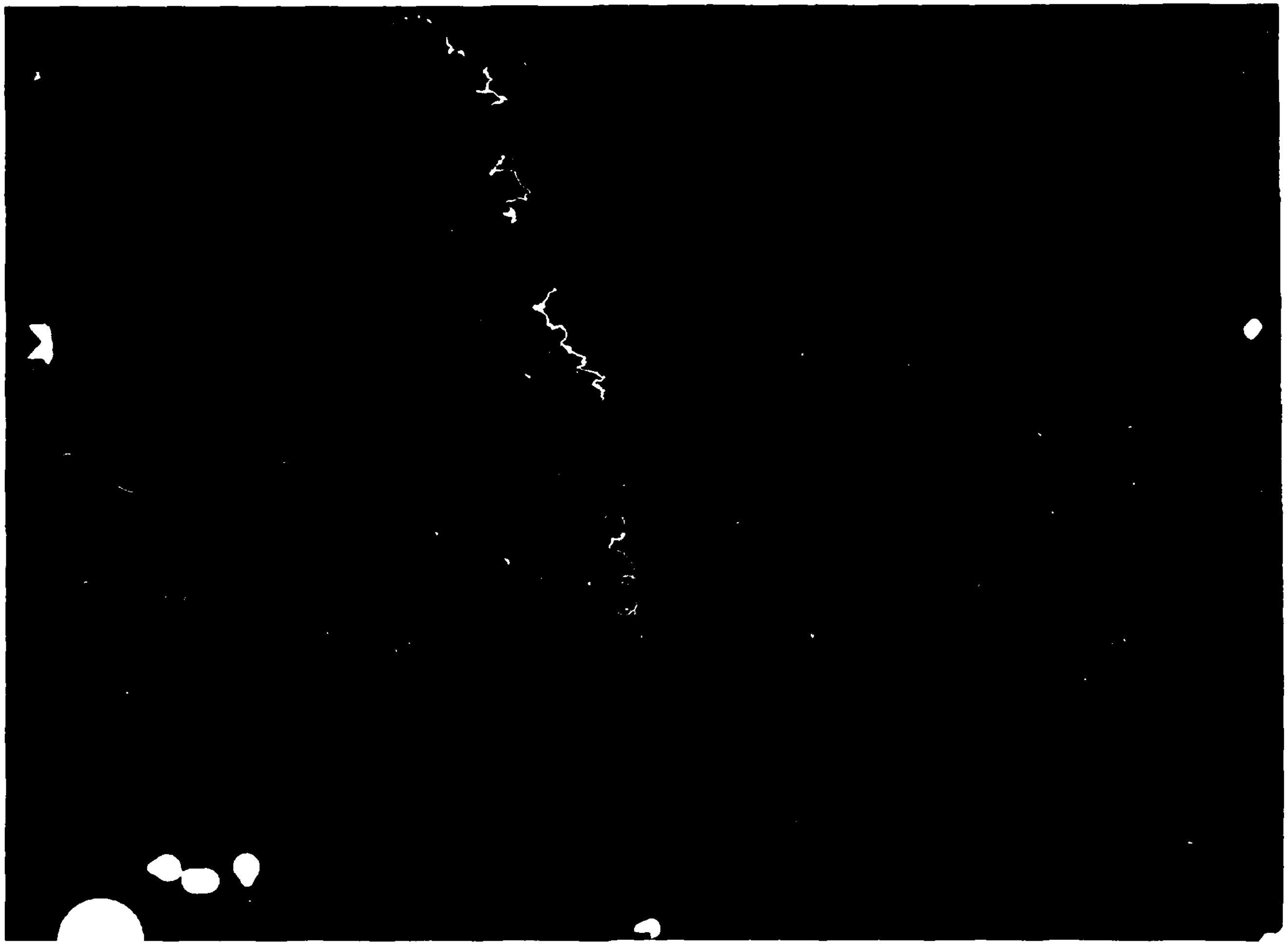

Figure 1. Triangulation photograph of trail 20 May 1978 taken from Pocomoke City, MD at t = 97 sec after rocket launch.

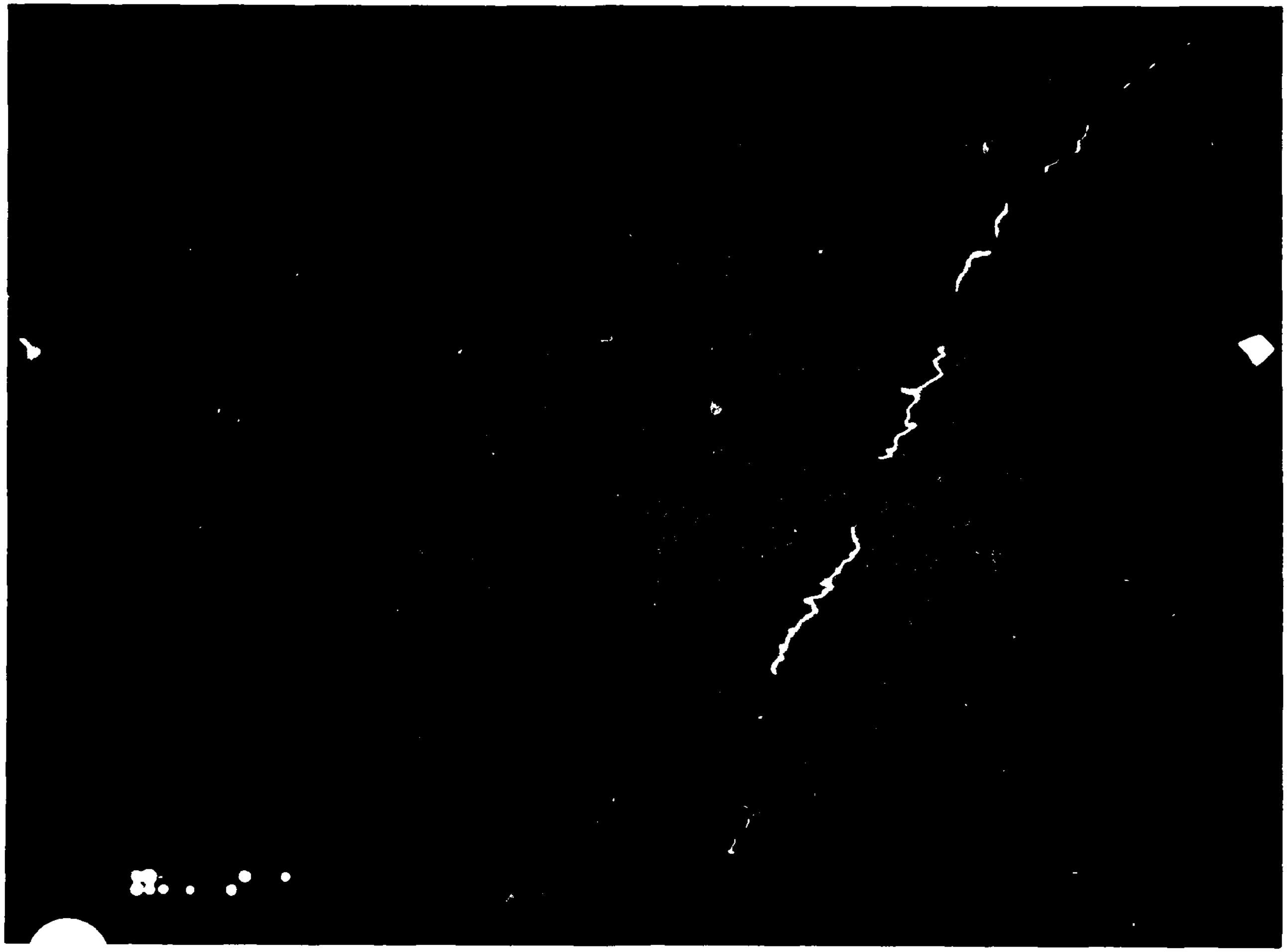

Figure 2. Triangulation photograph of trail 20 May 1978 taken from Wachapreague, VA at t = 97 sec after rocket launch.

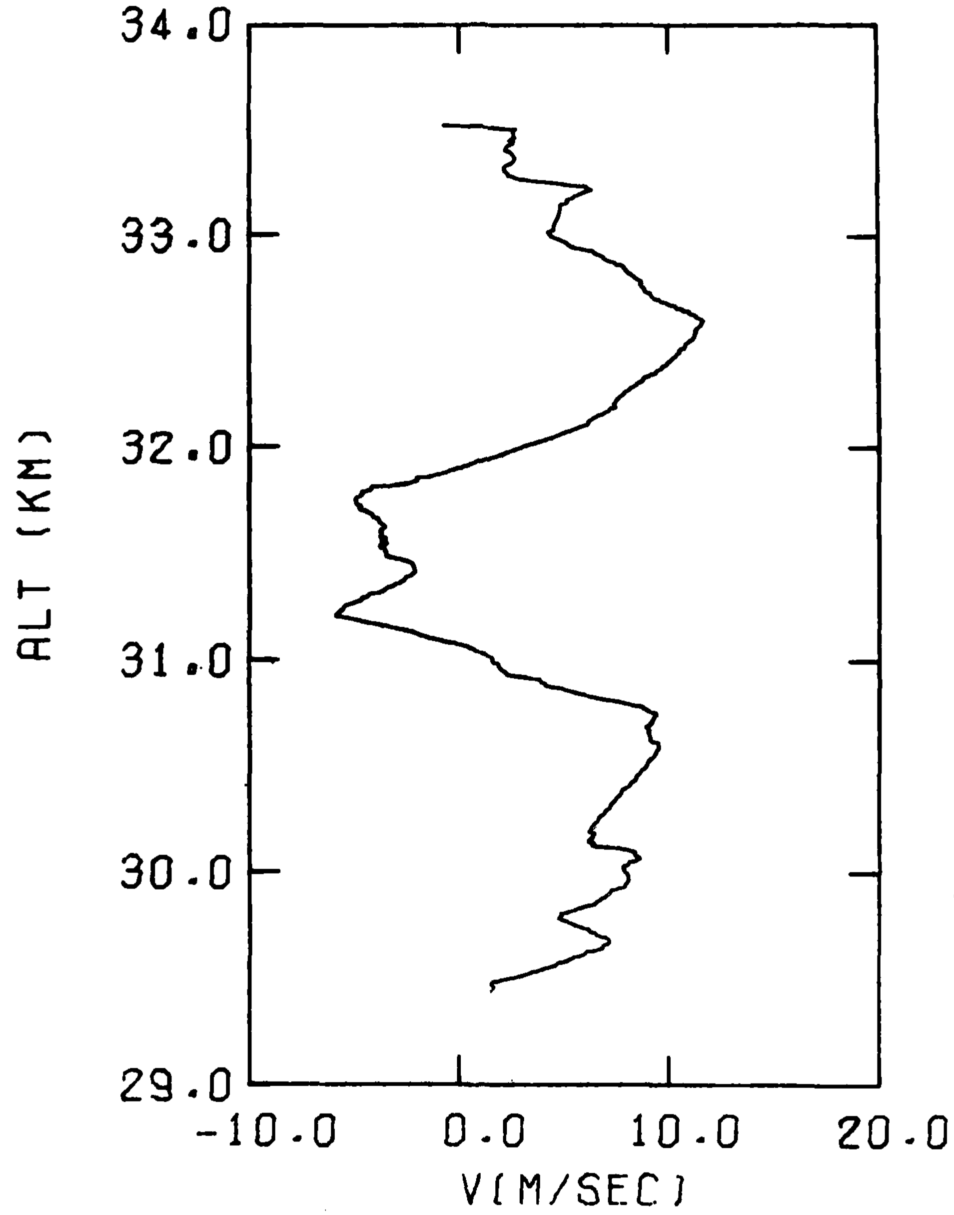

Figure 3. Easterly component of the stratospheric wind determined from trail 20 May 1978 Dash 3, 10 meter height resolution.

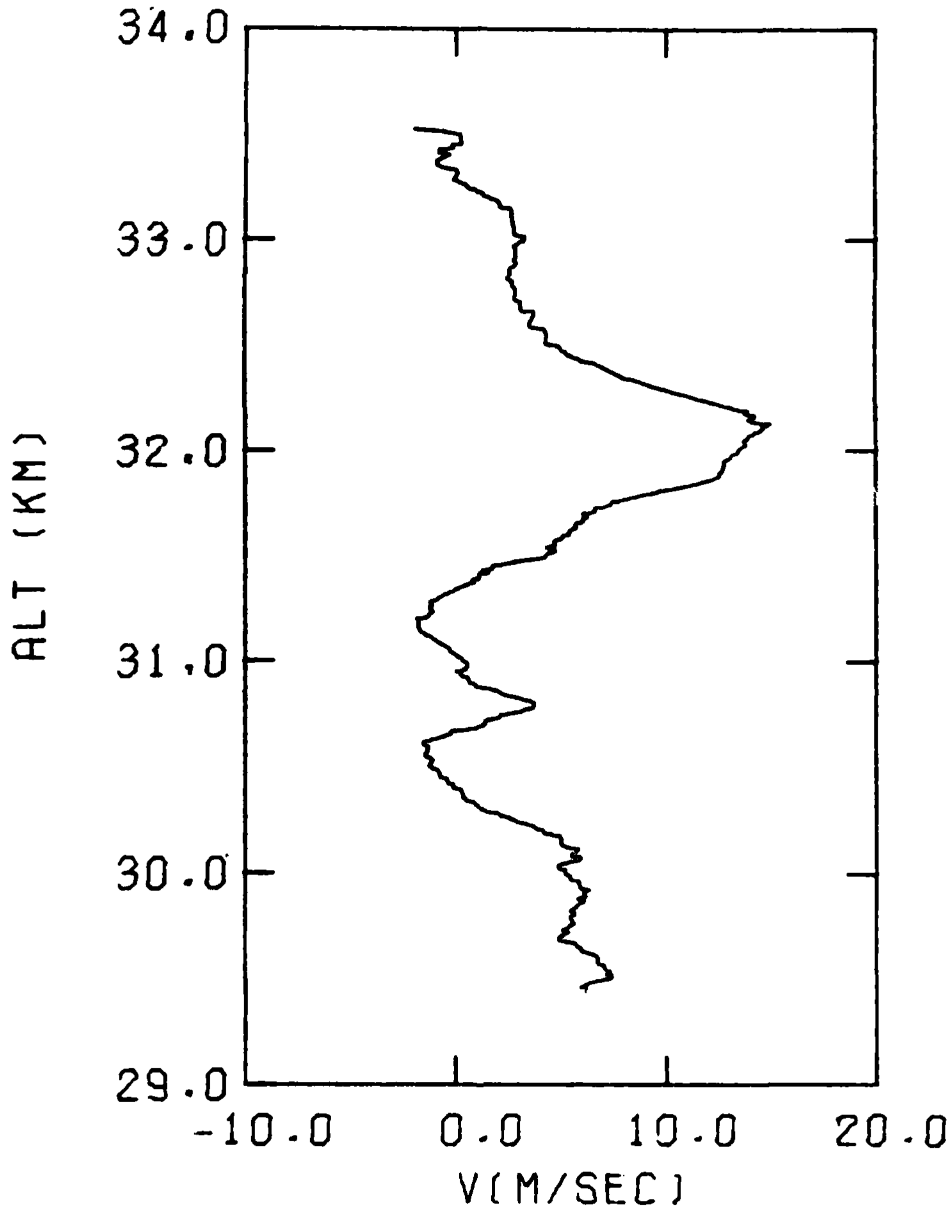

Figure 4. Northerly component of the stratospheric wind determined from trail 20 May 1978 Dash 3 at approximately 3 meter height resolution.

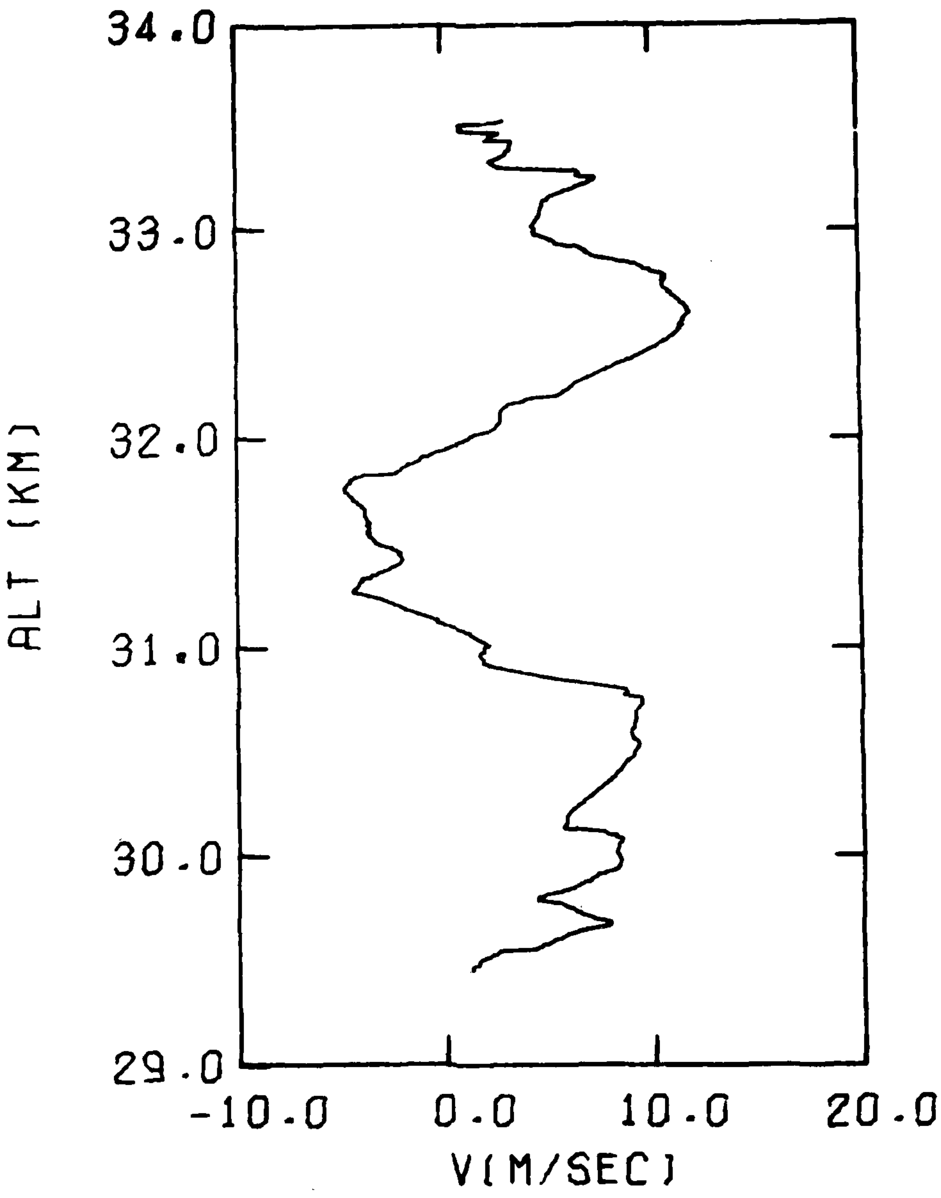

Figure 5. Easterly component of the stratospheric wind determined from trail 20 May 1978 Dash 3 at approximately 3 meter height resolution.

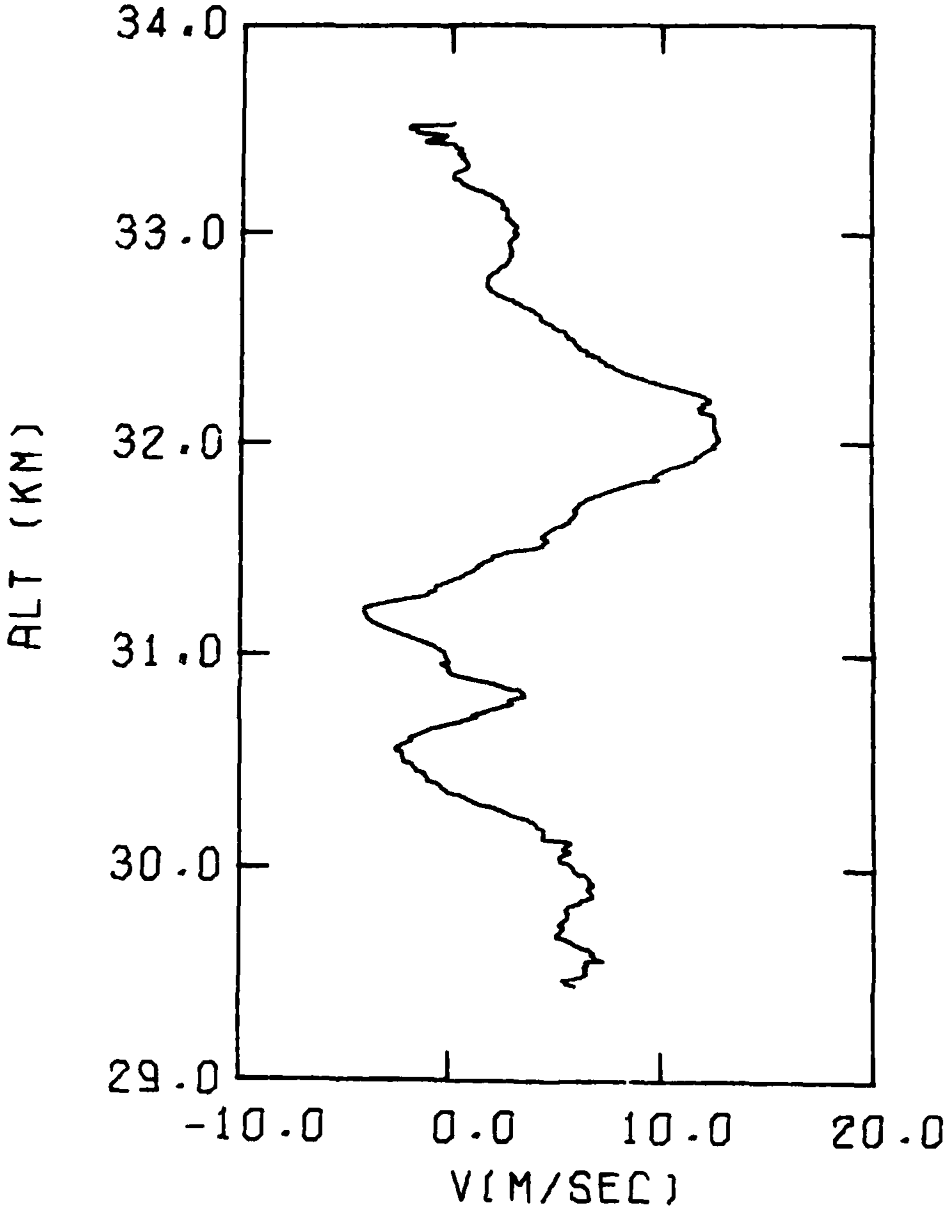

Figure 6. Northerly component of the stratospheric wind determined from trail 20 May 1978 Dash 3 at approximately 3 meter height resolution.

SECTION III

MAINTENANCE OF THE TRAIL DIGITIZATION SYSTEM

Maintenance of the Trail Digitization System hardware has posed increasing problems throughout the performance of this effort. The older portions of the system - that is, the original AFGL video Densitometer, which is ten years old - have been the source of repeated failures, and are becoming more difficult to repair with each failure. Equipment breakdowns, diagnosis of problems, and subsequent repair as detailed below has become an excessively large portion of the effort. The intermittent nature of many of the problems has also exacerbated the maintenance of the equipment.

The digital magnetic tape unit which serves the dual purpose of the system program input device to the computer and also provides the recording medium for the digitized trail positions has been the most frequent unit to fail. Repairs to this unit have included - replacement of the BOT/EOT sensor (twice); replacement of tape load relay; replacement of manual operation switches; replacement of read/record head; replacement of assorted transistors and tension arm sensor lamps; and isolation and repair of intermittent loss of low voltage power caused by poor contacts (twice).

The color video monitor which is used by the operator to properly adjust the density threshold controls was repaired several times for loss of high voltage to the CRT. Other repairs were performed to the R-G-B amplifiers and to a high voltage filter network. A further problem with video synchronization was not corrected since it has been decided to replace the monitor because of the overall poor quality of the displayed image.

The system computer which directs the operation of all of the other equipment has failed solely because of poor electrical contacts. These were usually caused by integrated circuit chips being moved slightly in their sockets by thermal expansion of the circuit package. In one instance a series of interconnecting plugs was replaced to eliminate a recurring contact problem. Poor connections have also been a source of a failure of the magnetic disk unit which stores the system program for on-line use and stores the digital video image. Further, several failures of the digital line buffer which provides the link between the computer and the disk were traced to similar problems.

Further compounding the complexity of maintenance of the digitization equipment is obsolescence. Replacement parts are becoming difficult to obtain and in some instances are unavailable.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

A total system for utilizing the smoke trail technique to accurately determine high resolution horizontal winds has been demonstrated. Routine calculations have been made of the horizontal stratospheric wind at a vertical resolution of 10 meters and a velocity standard deviation of approximately 0.5 m/sec. A test of higher resolution capability demonstrated a vertical resolution of 3 meters. It appears that resolution is presently limited to approximately 2 meters by the recording limit of the film and camera focal length combination. Film grain noise sets the limit to determining finer scale trail structure.

Vertical sampling of the wind field at approximately 1 m increments could be accomplished increasing the focal by a factor of two. On the other hand it appears that the accuracy of the camera orientation and focal length determinations now limit the resolution to approximately 10 meters. Increased accuracy in timing of the star calibration exposure should enable this latter limit to be reduced by at least a factor of 2.

Additional analysis was carried out to determine the vertical shear of the horizontal wind which presents a limited accuracy description of the degree of turbulence of the stratosphere. Calculation of better descriptor - the Richardson number of turbulence - requires an altitude profile of temperature, for example from a rawinsonde flown at nearly the same time and location as the trail. Rates of turbulent dissipation would also be calculable if rawinsonde temperature measurements were made an integral part of the experiment.

The smoke trail method can also be used to make significant contributions in the characterization of laser beam propagation through the atmosphere through experimental determination of C_n^2, the structure constant of atmospheric index of refraction variations.

C_n^2 is a measure of the variation of turbulence induced changes in the optical index of refraction. Estimates of C_n^2 as a function of altitude may be obtained from temperature and pressure data from a rawinsonde combined with wind profile derived turbulence lengths, eddy diffusivities, and momentum diffusivities.

Increased maintenance requirements of the trail digitization system hardware due to high failure rates of the old portion of the system have decreased the anticipated system throughput. It is suggested that replacement of the old components of the system would increase efficiency by reducing time spent in troubleshooting and repair with subsequent reduction in the time spent in digitizing each trail.

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